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The once and future pulse of Indian monsoonal climate

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Abstract We present a comprehensive assessment of the present and expected future pulse of the Indian monsoon climate based on observational and global climate model projections. The analysis supports the view that seasonal Indian monsoon rains in the latter half of the 21th century may not be materially different in abundance to that experienced today although their intensity and duration of wet and dry spells may change appreciably. Such an assessment comes with considerable uncertainty. With regard to temperature, however, we find that the Indian temperatures during the late 21st Century will very likely exceed the highest values experienced in the 130-year instrumental record of Indian data. This assessment comes with higher confidence than for rainfall because of the large spatial scale driving the thermal response of climate to greenhouse gas forcing. We also find that monsoon climate changes, especially temperature, could heighten human and crop mortality posing a socio-economic threat to the Indian subcontinent.

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1 Introduction

The subsistence of India's burgeoning population and the health of its emergent economy are intricately tied to the pulse of its monsoonal climate. Variability in agricultural output (about 22% of GDP) is largely driven by the year-to-year fluctuations in strength of the summer monsoon rains (June to September), accounting for the historical binding of Indian economic and social fabric to climate. We are thus compelled with more than academic interest to determine how human emissions of greenhouse gases may affect the future pulse of Indian monsoon rains. At issue is not only the overall volume of rains during the summer monsoon season, but also the length of the monsoon season, the manner in which those rains are delivered (such as the number of rainy days and their intensity which affects agronomic stress and yields), and the frequency of severe rains (especially tropical storms which have property and life implications). We present lines of evidence and offer physical explanations to support a view that the seasonal mean Indian monsoon rains in the latter half of the 21st century may not be materially different in *abundance* to that experienced today, although their *intensity and duration of wet/dry spells* may change appreciably. Such an assessment comes with considerable uncertainty, some reasons for which are also given.

The matter of temperature is rarely considered when assessing the historical vulnerability of India to climate, owing to the fact that India's subtropical geography has ensured great stability of its yearly temperatures—interannual swings are mostly less than 1°C. As such, rain rather than temperature has exposed underlying risks to Indian societal and agricultural concerns to date. To be sure, extreme wintertime cold waves and pre-monsoon heat waves have taken their tragic toll in lives and caused

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locally severe crop loss, but their consequences for greater India have paled when compared to fluctuations in the pulse rate of its monsoon rains.

With regard to temperature, however, history may prove to be a poor yardstick for potential impacts of anticipated future change on India. We present results that show Indian temperatures during the late 21st Century will very likely exceed the highest values experienced in the 130-year instrumental record of Indian data. This assessment comes with higher confidence than for rainfall because of the large spatial scale driving the thermal response of climate to greenhouse gas forcing. Indications of the response of human health and agricultural productivities to the late 21st century temperatures form a basis for discussion of the potentially large and detrimental effect that increases in greenhouse gases may have on the social and economic health of India.

2 Data and methodology

The historical variations in Indian climate are well documented by measurements of temperature and rainfall that have been collected from hundreds of stations having nearly complete records since the late 19th Century. These data have been aggregated to form an areal averaged index of climate; an All-India monthly rainfall set (Parthasarathy et al. 1992), and an All-India monthly Tmax and Tmin set, each spanning the period 1871–2007.[1] The All-India summer (June–Sep) monsoon rainfall index (AISMR) is computed from the monthly rainfall. We further utilize recent satellite estimates of rainfall (the so-called CMAP data of Xie and Arkin 1997) in order to describe the adjacent oceanic conditions of monsoon rainfall. Also, a global view of surface temperature including oceanic regions is generated using the University of East Anglia monthly gridded set (so-called HadCRU3v data) (Brohan et al. 2006).

We diagnose historical climate simulations and projections of climate to the end of the 21st Century. As part of the Fourth Assessment activity of the Intergovernmental Panel on Climate Change (IPCC), numerous modeling centers conducted coupled ocean–atmosphere simulations spanning the late 19th Century to 2100. Here we analyze 22 of these models (48 simulations) that are forced with estimated greenhouse gas and aerosol changes from the late 19th century through 1999, and then employing the IPCC Special Report on Emissions Scenarios (SRES) A1B scenario to 2100.

Additionally, a high resolution simulation of Indian regional climate, using the Hadley Centre for Climate Prediction of UK Meteorological Office model (PRECIS), is diagnosed with so-called time-slice experiments that have been performed using two sets of lateral and surface boundary forcing data generated from the Hadley Centre's global coupled model: one corresponding to the present (1961–90) with observed GHG forcing, (the 'baseline' run), and the other for the future (2071–2100) following SRES-A2 emission scenario. Details of the regional model, its domain, its simulated seasonal climatology and its variability are discussed in (Rupa Kumar et al. 2006).

3 Historical pulse of the Indian monsoon

India's summer rains are most remarkable for their great reliability, generally within 10% of historical normal, the well-documented years of monsoon famine or flooding notwithstanding (Fig. 1, top). Some of the more extreme spikes in this otherwise steady pulse have occurred in tandem with El Niño, a natural phenomenon that is characterized by sea surface warming of the equatorial east Pacific Ocean (Sikka 1980; Kumar et al. 1999, 2006). As highlighted by vertical red bars, the majority of all extreme monsoon failures have been associated with El Niño events. This is an important characteristic of the natural sensitivity of India's monsoon pulse. First, because it forms a basis for drought early warning systems that serve to mitigate climate impacts from year-to-year (Kumar et al. 1995). Second, because human-induced future climate change will include warming of the tropical oceans, thereby creating opportunities for science to anticipate the implications for future monsoon intensity. The nature and impacts of future oceanic warming on the Indian monsoon are subsequently discussed. Lest the case for an oceanic driving of the Indian monsoon be overstated, however, it should also be noted in Fig. 1 that substantial variability of monsoon strength has been witnessed even when El Niño is absent. In other words, chaotic internal atmospheric variations, and other boundary forcings also explain an important fraction of monsoon rain variability. The implication is that a significant fraction of the yearly variations in monsoon pulse cannot currently be anticipated (Kumar et al. 2005; Goswami 1998).

A moving 31-year filter applied to the AISMR (All-India Summer Monsoon Rainfall) data highlights the lower frequency behavior of the monsoon pulse (Pant and Rupa Kumar 1997). First, no 31-year period has witnessed rains departing from the long term climatology by more than 5%. Nonetheless, even these modest epochs of slightly more vigorous or weaker monsoon pulse can be consequential, and have therefore been the focus of ongoing scientific inquiry. For instance, the epochal nature of India's 20th century wet and dry regimes is believed to be

[1] http://www.tropmet.res.in.

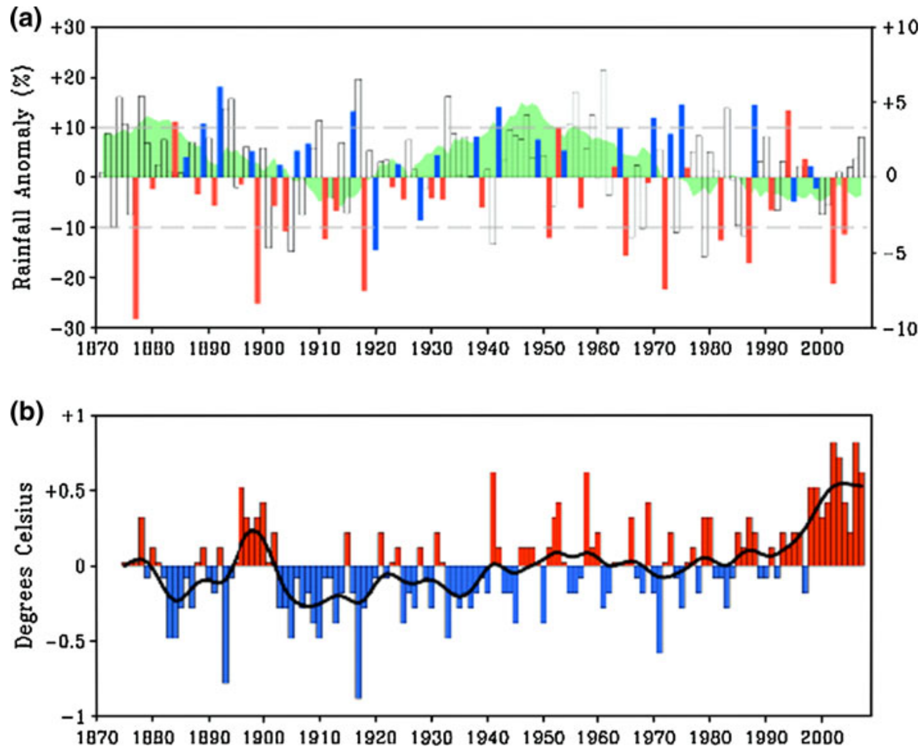

Fig. 1 **a** All-India Summer (JJAS) Monsoon rainfall anomalies (% of 1961–1990 mean) during 1871–2007. The 31-year sliding mean of the anomalies is shown in *green shaded curve*. The *red/blue bars* indicate El Niño/La Niña years, respectively. **b** All India annual surface temperature anomalies (respect to 1961–1990 mean) during 1875–2007. 31-year sliding mean is shown as *thick black line*

driven in part by epochal variations of El Niño frequency (Kripalani and Kulkarni 1997a, b; Slingo 1999) and corresponding epochal swings between warm and cold periods of the North Atlantic Ocean (Goswami et al. 2006a). The recent period of below normal rainfall (longer than witnessed in the past), coming especially on the heels of a prolonged wet period, has raised some concerns whether climate change may now be weakening the Indian monsoon pulse. However, we will show that the anthropogenic impact on future monsoon intensity is likely to favor more abundant rains, as also highlighted recently in the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2007). Atmospheric aerosols in Asia seem to be another factor impacting the Indian monsoon. Some recent studies (Lau et al. 2008; Ramanathan et al. 2005; Meehl et al. 2008) indicate this association from observational and modeling experiments. The exact role of aerosols on the low-frequency decadal monsoon variability is yet to be established.

Other important features of monsoon rainfall that appears to be undergoing change owing in part to anthropogenic forcing (Goswami et al. 2006b) is the increasing trend in the magnitude and frequency of extreme rainfall events during post-1950 period across Central India. They also show a corresponding decrease in the frequency of low rainfall events. This redistribution of rainfall character has implications for flood and water resources management, and we will present new calculations using a regional model that confirm such characteristics of the monsoon rainfall delivery to become typical in the latter half of the 21st Century.

Generally less attention is given to an index of All-India surface temperature, mainly because of its much muted interannual variability (Fig. 1, bottom). Indeed, there has been little evidence for a trend in surface air temperature over India until perhaps the mid-1990s when night time temperatures (Tmin) started increasing at twice the rate of day time temperatures (Tmax) resulting in 6 of the 10 warmest years on record (Padma Kumari et al. 2007; Kothawale and Rupa Kumar 2005). We will subsequently demonstrate, using climate models, that an emergent warming signal approximately at this period of the late 20th Century is consistent with an anthropogenic signal.

4 Future pulse of the Indian monsoon

A principal tool for probing the likely future pulse of the monsoon involves simulations with climate models subjected to radiative forcing associated with human emissions of greenhouse gases. The suitability of such models is not easily demonstrated. This is because no historical condition of monsoon climate under the influence of doubled atmospheric carbon dioxide concentrations exists against which modeled responses might be validated. A further complication is that the physical processes controlling the monsoon response to increased greenhouse gas forcing are not well known; neither the forcing-response relationships nor the feedbacks are completely understood. Nonetheless, it is generally assumed that a prerequisite for the use of such models be that they faithfully produce the known features of climate and its variability. Several studies have assessed such performance metrics of different climate models, for instance, ones that are not coupled to the ocean but forced by specified sea surface temperature (SST) conditions (Kumar et al. 2005; Gadgil and Sajani 1998; Wang et al. 2004) and ones fully coupled and interactive with the underlying oceans (Annamalai et al. 2007; Kripalani et al. 2007). These efforts sought to validate the suitability of models for either seasonal forecasting purposes or for climate change projection purposes. Consistent with the discussion above, these studies have not resulted in a unique subset of "best models". As such, there is little current justification for not using the full suite of available climate models and developing multi-model ensembles to assess future changes. Indeed, other studies for weather and seasonal forecasting have highlighted the attributes of so-called multi-model super ensemble methods as a means to provide the best estimate of the predictable signal and to quantify its uncertainty (Palmer et al. 2004; Krishnamurthy et al. 1999; Rajagopalan et al. 2002). Such an approach has also been advocated by IPCC-AR4 WG1 (Chapters 8 and 10) who state that "the reason to focus on the multi-model mean is that averages across structurally different models empirically show better large-scale agreement with observations, because individual model biases tend to cancel". Consequently, in this paper we use the multi-model ensemble to assess the future monsoon climate change and refrain from selecting a model subset.

We find good agreement between the observed and simulated climatological Indian monsoon rainfall distribution (Fig. 2), its annual cycle (Fig. 3, middle right), its standard deviation (Fig. 3, bottom right), and its sensitivity to ENSO (Fig. 3, bottom right). The map-to-map correlations between the observed and model simulated rainfall and temperature fields shown in Fig. 2 exceed 0.79 and are significant at 99% confidence level. The most notable deficiency of the multi-model averaged monsoon rainfall is that the total June–September volume is about 20% lower than observed. This is partly an outcome of the low rainfall along coastal western India where the Ghats (Mountains) lead to large orographic enhancement in nature, but is diminished owing to the coarsely resolved terrain in the global models (see Fig. 2). The box/whisker plots of Fig. 3 summarize the range of model values for two key features of AISMR rainfall fluctuations; its average yearly variability (about 80 mm observed) and its statistical correlation with ENSO-SST (NINO3) variations in the tropical east Pacific (about −0.5 observed). The median values of the various model simulations yields roughly 70 mm for the interannual variability, and an ENSO-SST correlation of −0.4, both remarkably close to observed. To be sure,

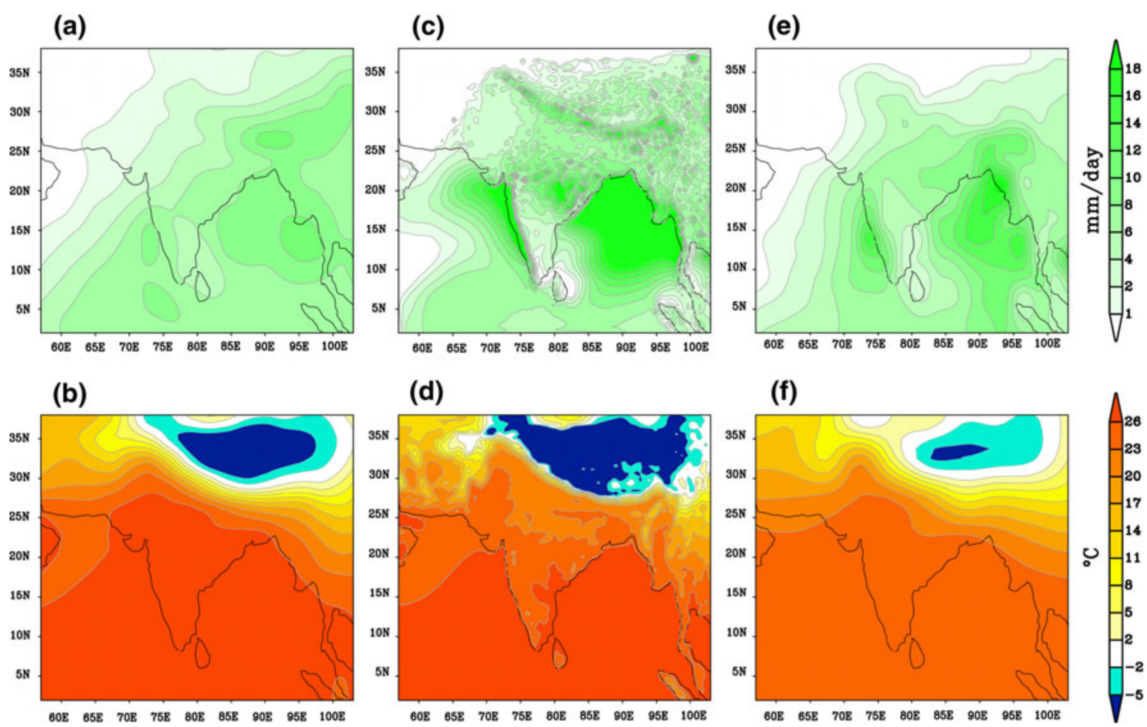

Fig. 2 Monsoon (JJAS) rainfall and annual temperature climatologies for the IPCC-AR4 model ensemble mean for the period 1961–1990 (**a**, **b**); PRECIS (**c**, **d**) and observed (**e**, **f**)

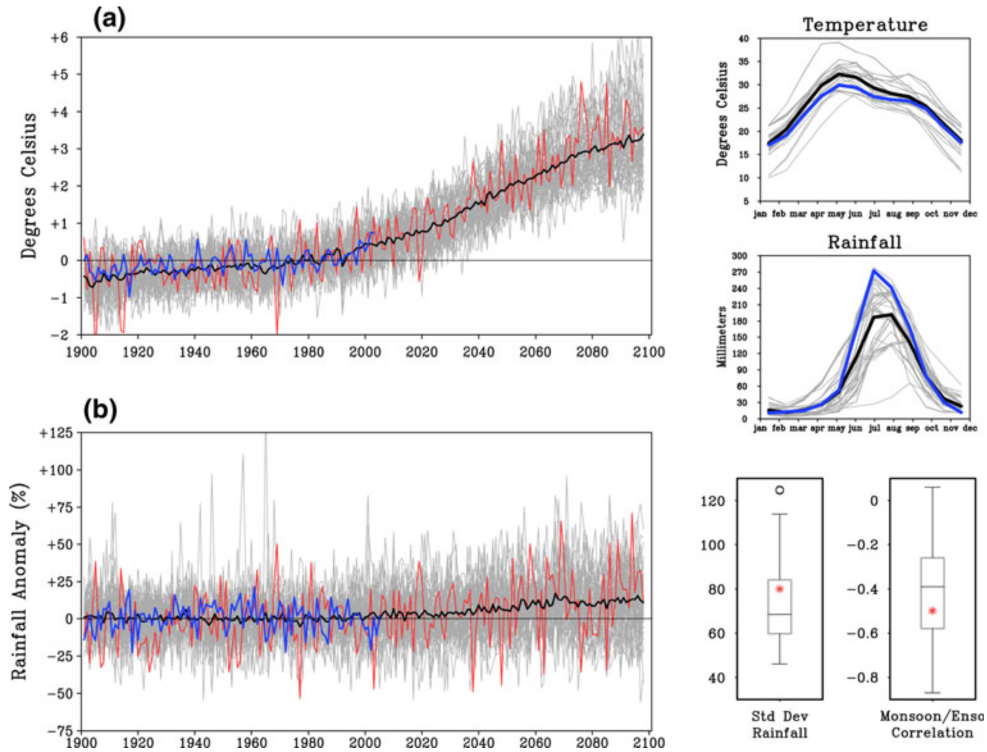

Fig. 3 IPCC-AR4 simulations for the 1901–2098 period—**a** Annual surface temperature over India and **b** Monsoon rainfall over India. The *grey lines* indicate the ensemble, the *black line* is the ensemble mean and the *blue line* is the observed. The *red line* is the ensemble member corresponding to the Hadley Center coupled model. The *right hand figures* show the annual cycle of temperature and rainfall over India and, *boxplots* of standard deviation (mm) and monsoon-ENSO correlation, for the observational (1901–2000) period. The observed values are shown as *red points* in the *boxplots*

there is a large spread among the models as indicated by the vertical whiskers, with some models having no ENSO correlation, and some models having only half the observed rainfall variability. In aggregate, however, our assessment is that the multi-model ensemble mean offers a good representation of several principal, verifiable features of Indian monsoon rainfall.

Regarding surface temperature, the agreement is also good. The observed annual cycle is noteworthy for its pre-monsoon maximum, a feature captured in the ensemble mean, and in all individual runs (Fig. 3, top right). The simulated climatology exhibits a warm bias of about +1 to +2°C mainly during the pre-monsoon and monsoon seasons, which during the latter period may be a consequence of the aforementioned model dry bias. Overall, the simulations offer a realistic construction of current Indian temperature. It should be noted that in all subsequent analyses of anomalies in simulated Indian climate for the 21st century, departures are computed with respect to the model's climatology, thereby providing a simple linear removal of the model biases discussed above.

The simulated annual temperature and monsoon season rainfall, averaged over the Indian land grids from the ensembles for the 1901–2098 period is shown in Fig. 3a, b, respectively. The observed variability up to 2005 (blue line) falls well within the spread of the individual model simulations (grey cloud) and is further well described by the model ensemble mean (black line). The most striking feature of the projections to 2098 is the increase in annual surface temperature, with an ensemble mean signal of +2°C by mid 21st century and +3.5°C by century's end. While there is amplitude uncertainty, with the range at 2098 being +2°C to +6°C, all simulations increase Indian temperatures far beyond any annual values measured during the last 100 years. This substantial warming can have a significant manifestation in the variability of extremes that could be detrimental to socio-economic activity. This will be examined in the following section when we analyze results from the regional model simulations. These additional experiments were forced at the lateral boundaries by conditions drawn from the Hadley Center global model whose simulated conditions (red line) are very close to the ensemble mean for India.

Compared to temperature, the projected monsoon rainfall change bears considerably less certainty. Whereas the ensemble mean signal is for increased rainfall by 2098 of +8 to +10%, there are a significant collection of simulations that actually project less rainfall at century's end. Furthermore, the signal estimated from the ensemble mean is not appreciably greater than the 20th Century observed interannual variability. If the ensemble mean were the true expected signal due to greenhouse gas forcing, then its detectability in the single time series of future monsoon rain will be quite low. Much of the increase is projected to occur during the second half of the century, further suggesting a discernable change in total Indian monsoon rainfall would be deferred for some time.

Several other important features of the monsoon rainfall are also examined, including the variability and seasonality of the projected rainfall (Fig. 4a, b). The ensemble mean annual cycle of rainfall for the present (1961–1990) and future (2070–2098) indicate a nearly 20% increase during May and October, the current flank periods of the monsoon. This is suggestive of an extended monsoon season in the future and is consistent with findings in other recent studies (Meehl et al. 2006, Kripalani et al. 2007; Chung and Ramananthan 2007).

The standard deviation of monsoon rainfall and the strength of the monsoon-ENSO correlation during the three periods (1961–90, 2041–60 and 2070–2098, box plots in Fig. 4c, d) indicate a slight increase ($\sim$10%) in the standard deviation in the future compared to the present period. In contrast, the monsoon-ENSO correlation appears to be quite stable. This assessment, based on the entire suite of IPCC model runs, is in variance with earlier studies that have indicated considerable changes in monsoon rainfall variability and its ENSO teleconnection in the future (Ashrit et al. 2003; Meehl et al. 2006; Annamalai et al. 2007; Kripalani et al. 2007; Turner et al. 2007). We believe this difference is due to the fact that those studies used a single or a small subset of models. It should be noted that the current generation of IPCC models have serious systematic errors in both the simulated mean and variability of ENSO (IPCC 2007; Latif and Keenlyside 2009). Potential changes in the flavors of ENSO that have been shown to influence Indian monsoon (Kumar et al. 2006; Ashok et al. 2007) are examined in detail in a recent study by Yeh et al. (2009).

Spatial patterns of the projected change in June–September rainfall and in annual surface temperatures at the end of the 21st century relative to present are shown in Fig. 5. As is now well known from the various IPCC reports, the primary warming is expected to occur over land. This continues a trend that has already been observed during the last several decades. Over the oceans, sea surface warming is weaker and somewhat more uniform, though a maximum along the equatorial Pacific is reminiscent of an El Niño like pattern seen on interannual time scales. There is a debate as to the cause for such an El Niño-like warming response of SSTs to greenhouse gas emissions (Vecchi and Soden 2007), though this feature is robust among various models. This is a matter of considerable interest for India since El Niño has historically induced drought conditions over the sub-continent on interannual time scales. Yet, as indicated in the top panel of Fig. 5, despite the canonical response of rainfall over the equatorial Pacific domain to El Niño-like warmth at 2098, India and much of Southeast Asia are projected to experience increased rainfall, opposite to a typical El Niño drought signal.

Given that El Niño is the primary predictor for year-to-year swings in AISMR, it is important to understand why a future Pacific SST change resembling El Niño conditions fails to weaken the pulse of India's monsoon. This apparent paradox can be explained by examining atmospheric circulation and moisture indices that monitor monsoon intensity. The evolution of a meridional wind index (Goswami et al. 1999) over the Indian subcontinent derived

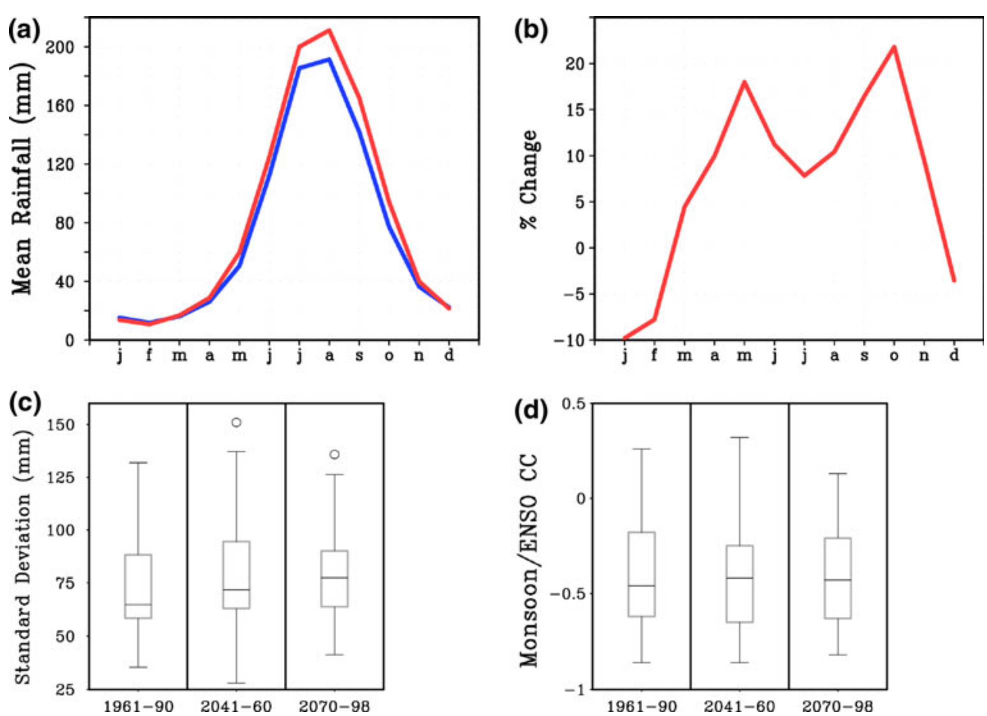

Fig. 4 **a** IPCC-AR4 ensemble mean monthly rainfall climatology of present (1961–1990) period (*blue*) and future (2070–2098) period (*red*). **b** Percent change in mean monthly rainfall in future relative to present. **c** *Boxplots* of standard deviation (mm) from the CMIP simulations for 1961–1990, 2041–2060 and 2070–2098 periods. **d** Same as (**c**) but for monsoon-ENSO correlation

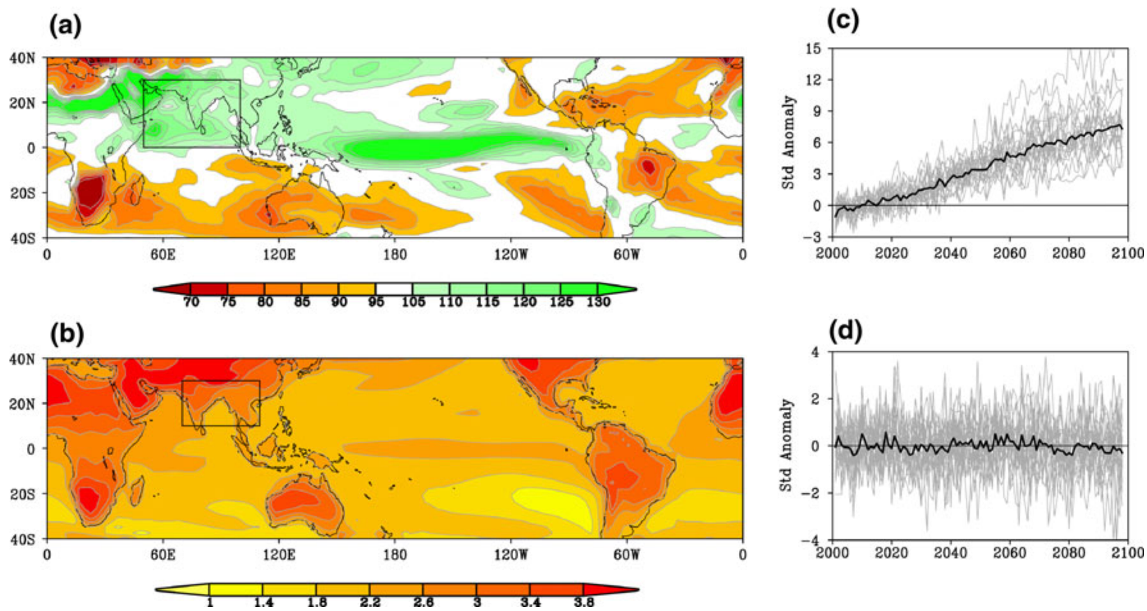

Fig. 5 **a** Percent change of ensemble mean monsoon rainfall in future (2070–2098) with respect to present (1961–1990). **b** Ensemble mean annual temperature change in the future. **c** Standardized anomalies of total column precipitable water averaged over the domain shown in (**a**)—simulated from 19 models (one ensemble member per model) during 2001–2098. **d** Standardized anomaly of meridional wind index (v-wind difference between 850 and 200 hPa) averaged over the domain shown in (**b**)—simulated from 21 models during 2001–2098. Standardization is done based on the mean and standard deviations of each model during the period 2001–2020

from the multi-model ensemble mean for the period 2000–2098 is shown in Fig. 5d. This index captures the strength of the low level and upper level wind circulation that sustains the transports of heat and moisture into the monsoon region, and is defined as the vertical difference in meridional wind between 850 and 200 hPa. As can be seen, there is no trend in the strength of this dynamical index during the entire 21st century suggesting no perceptible change in the strength of the monsoon circulation. Another indicator of monsoon intensity is the meridional gradient in tropospheric air temperatures between the Indian Ocean and the Asian continent (Goswami et al. 1999). Despite the increase in *surface* temperature contrast between these regions related to the greater land surface warming, we find no change in the simulated tropospheric temperature contrast (not shown). These indicators point to a monsoon circulation in the future having intensity similar to that seen today, despite El Niño like conditions in the tropical Pacific. Of course, the intensity of that circulation is intimately coupled to the monsoon rains itself, and we have yet to explain why those rains fail to slacken in light of the tropical Pacific warm ocean conditions. Perhaps a major mitigating factor is the projected change in atmospheric water vapor content. Figure 5c illustrates the very large increase in water vapor over the greater monsoon region, likely due to increases in temperature and evaporation (IPCC 2007). The convergence of this additional moisture over India within the lateral branches of the monsoon circulation would alone lead to enhanced rainfall, and we surmise is a principal reason for the overall Indian monsoon rainfall increase. Sensitivity experiments using individual climate models of monsoon rainfall changes in the future under increased GHG forcing also suggest enhanced thermodynamical changes that act to favor an abundance of monsoon rainfall (i.e., more moisture available in the atmosphere) (Meehl and Arblaster 2003; Sugi and Yoshimura 2004; Dairaku and Emori 2006).

5 Societal implications

Indian society with modest infrastructure is highly vulnerable to even slight variations in weather extremes. This is highlighted by an increasing occurrence of extreme events, extracting heavy toll on the economic and social health of India, in recent periods such as—floods across many states during 2005–07, the remarkable 944 mm one-day rainfall on 26 July, 2005 at Mumbai; high human mortality due to heat waves in 2003, to name a few. The possibility of increased weather extremes in the future has been reported from analyses of coarse resolution global climate models (May 2004; Sun et al. 2006). However, high resolution models are arguably better suited to investigate the variability in extreme weather conditions as they can better represent the spatial scales at which such systems develop (Diffenbaugh et al. 2005).

The High-resolution Regional Climate Model (PRECIS) simulations show significant changes in spatio-temporal patterns of extremes in daily Tmax and Tmin and rainfall characteristics that may have significant implications for crop production, water resources management and public health. For example, the expected future changes in Tmax under the A2 emissions scenario during the later part of 21st century indicate an exceedance of +4°C in many places in northern India, with average daily highs in the pre-monsoon season expected to routinely exceed 45°C (Fig. 6a, b). Similar increases are noted in the daily lowest Tmax, highest Tmin and lowest Tmin across the country in the future (figures not shown).

Model results also indicate a general increase in the extreme precipitation amounts in the future, though it should be noted that even for this regional model daily precipitation extremes are underestimated when compared to 20th Century observations A reduction in the number of rainy days and an increase in the intensity of rainfall shown over many parts of India (Fig. 6c, d) will have direct implications for water resources particularly floods and associated losses to agriculture, infrastructure damage and in public health. These results are based on a single high-resolution regional simulation and need to be further validated with an ensemble of simulations from a large suite of regional climate models.

Indian agricultural production and consequently, the country's GDP, show a strong link with monsoon rainfall (Kumar et al. 2004; Gadgil and Gadgil 2006). Despite this strong link, temperature variations play an equally critical role in crop production. For example, the direct and indirect effects of aerosols on the declining rice yields over India—mainly via temperature changes have been shown by Auffhammer et al. (2006). An increase of night time temperature of 1°C has been shown to result in a 10% reduction of rice yields in Philippines (Peng et al. 2004). Some recent studies (Welch et al. 2010; Nagarajan et al. 2010) show that night time temperatures beyond a

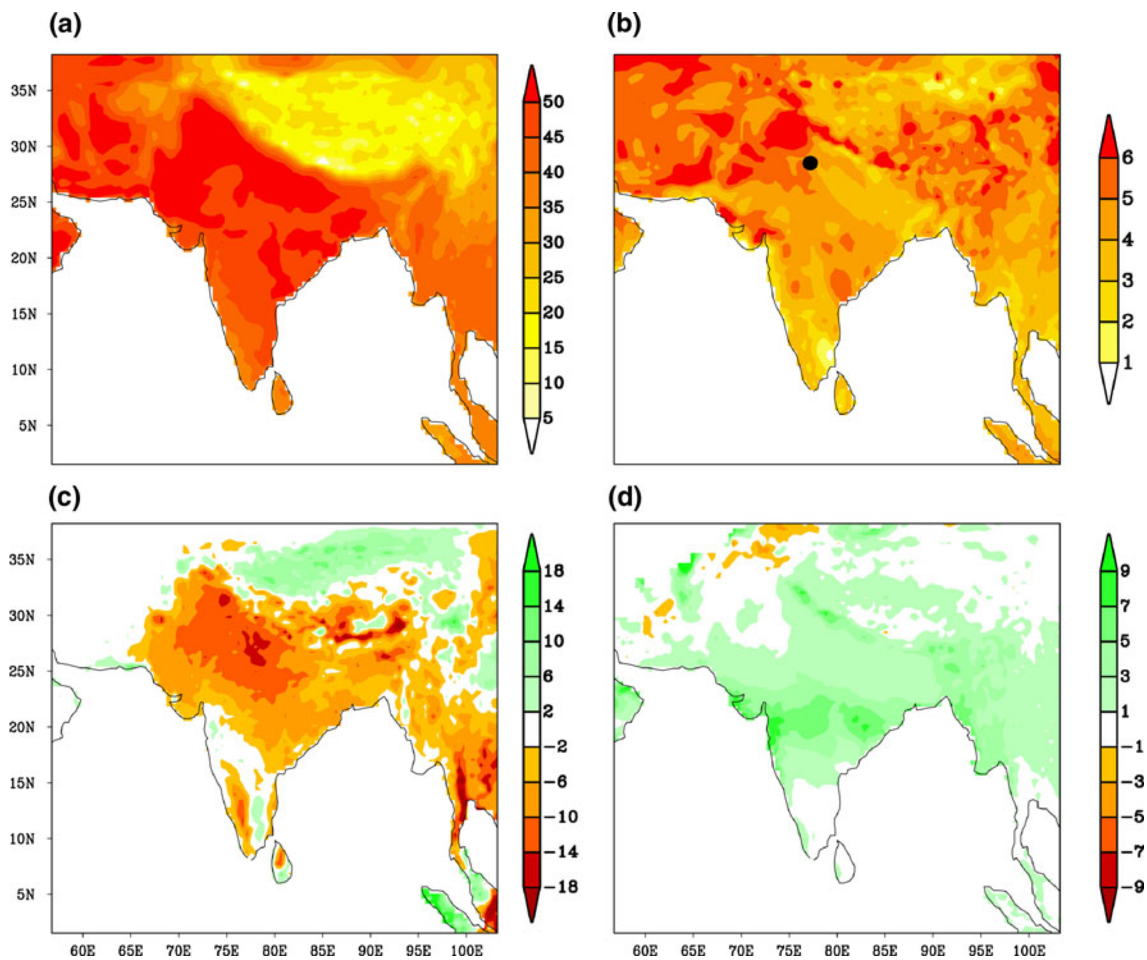

Fig. 6 Projected changes in daily maximum (Tmax) temperature and some aspects of daily rainfall based on simulations from PRECIS. **a** Pre-monsoon (March–June) Tmax for the baseline period (1961–1990). **b** projected future (2071–2100 minus 1961–1990 mean) change. The location of New Delhi is marked with a black dot in (**b**). **c** Projected future change in number of rainy days (days with rainfall >2.5 mm) during monsoon season and **d** the projected change in the intensity (mm/day) of rainfall on a rainy day

threshold can have stronger negative impacts on rice yields compared to radiation and day time temperatures over India and other parts of south Asia. These studies and those pertaining to other cereal crops (Lobell 2007; Lobell and Field 2007) bring to the fore the importance of changing temperatures on the yields of major crops that are grown in this part of the world.

The nonlinear relationship between all-India Kharif (rainy season) rice yields and the two important meteorological variables—growing season, (i.e., June–September) rainfall and Tmin during 1961–2007 is shown in Fig. 7a. The yield anomalies in % (shaded contours in the figure) tend to decrease with higher Tmin even with high rainfall. The lower yields under low rainfall are much more aggravated with higher temperatures. Thus, higher temperatures seem to reduce the yields regardless of rainfall—consistent with the findings of (Peng et al. 2004). A shift of nearly +5°C in the PDF of Tmin is found between baseline and late 21st Century simulations for a grid cell near New Delhi representing the Rice growing Indo-Gangetic Plains, a condition that would likely severely curtail future rice yields barring mitigation efforts (Fig. 7b). Similar warming shifts were also seen in the PDFs of day-time temperatures, a condition that could likewise have significant negative implications for wheat yields (Lobell and Field 2007).

Not withstanding the positive benefits that may occur in crop yields under increasing CO_2 (Aggarwal and Mall 2002; Long et al. 2006), the substantial increase in temperatures could result in a net loss of productivity in the coming decades barring mitigation. Though we do not wish to extrapolate the production losses based on (Peng et al. 2004), who estimate a 10% loss to every +1°C change in night-time temperatures, we surmise that even a decline of only 20% from current levels could be very consequential. We do not rule out the possibility of adaptation and development of new cultivars which are more heat resistant, but the challenge to compensate for the temperature related losses may not be easy. With the population of India expected to reach 1.6 billion by the mid 21st Century, the yields of major crops like rice and wheat would need to increase 50–100% from current levels to achieve food security (Govt. of India, India's Initial NATCOM 2004). The fact that there is already stagnation in the growth of area under cultivation and food production points to the challenges ahead (Milesi et al. 2010). Projected trends in temperatures could alone be a major deterrent to achieving

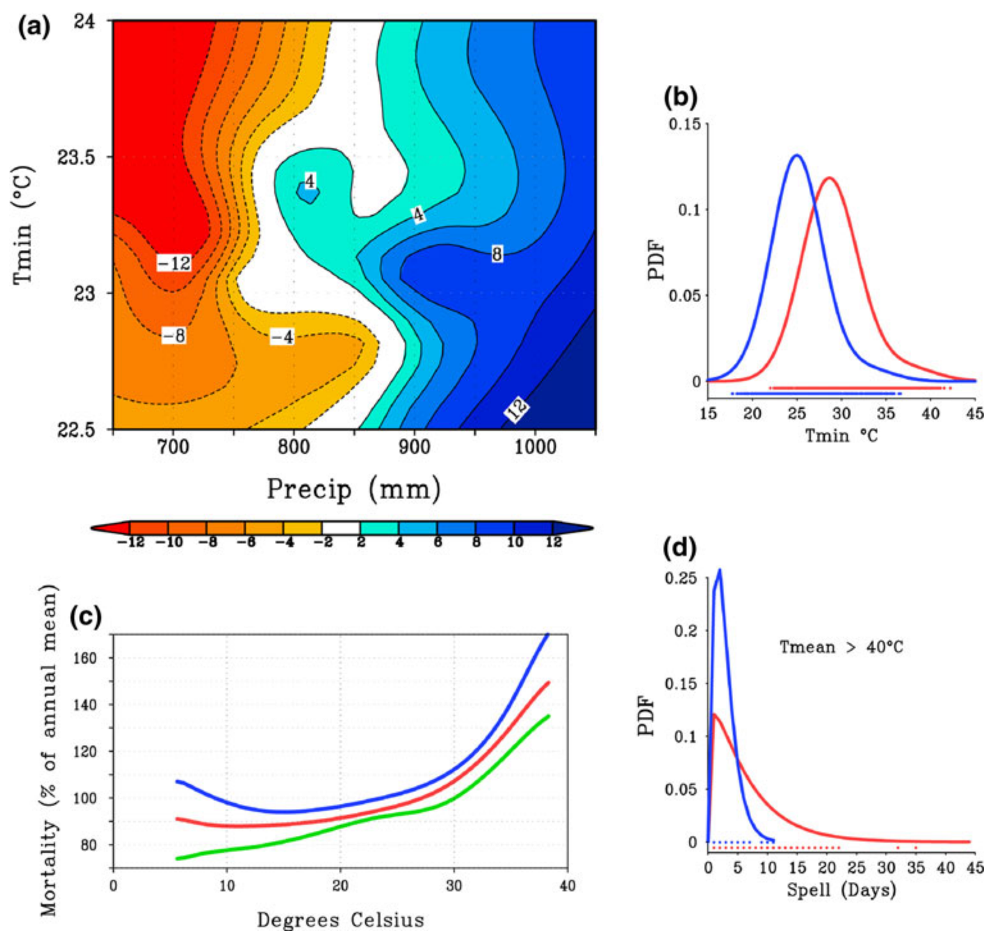

Fig. 7 **a** All India Kharif (rainy season) Rice yield anomalies (%—shaded contours in the figure) as a function of growing season (June–September) rainfall (X-axis) and average Tmin (Y-axis) over India. **b** PDF of Tmin from PRECIS simulation for the baseline (*blue*) and future (*red*) period. **c** Natural cubic spline regression curve (*red*) for daily mortality in New Delhi as a function of mean temperature during two consecutive days. The *blue* and *green curves* are the 95% confidence intervals. **d** PDF of mean temperature spells (in days) exceeding 40°C

this objective. Such a situation of decreasing yields coupled with increasing population could be a major socio-economic issue.

Another important impact of rising temperatures is on heat related mortality and morbidity. Each year many people die in India due to heat waves during the pre-monsoon season (Govt. of Andhra Pradesh Report 2004; Bhadram et al. 2005). There is a general misconception that people living in tropical climates have higher levels of heat tolerance and consequently, this impact of temperature is often neglected. While examining heat-related mortality in three major cities (New Delhi, Sao Paulo, London), the mortality risk due to heat exposure was found to be highest for New Delhi (Shakoor et al. 2005; McMichael et al. 2008) and Fig. 7c, (based on personal communication and data from Shakoor Hazat) with a steep increase in mortality rate beyond a mean temperature of 40°C for two consecutive days. Our analysis of regional model runs for a grid cell near New Delhi show a significant shift towards higher mean daily temperatures in the future, much like that seen in the daily Tmin (Fig. 7b). The PDF of mean temperature spells (i.e., number of days) exceeding 40°C at New Delhi in the baseline and late 21st Century periods are shown in Fig. 7d. In the base line the maximum spell is of the order of 12 days, but in future it is as high as 45 days long. The PDF of the future clearly indicates increased probability of longer extreme temperature spells, and barring mitigation efforts, would be expected to be very detrimental for public health. Such potentially dire shifts could be likely at other locations around the country with a potential to stress an already fragile public health system.

6 Conclusions

We can conclude with considerable confidence that the near term future (i.e., end of 21st century) would witness substantial increases in both day and night temperatures and increase in frequency and intensity of extremes. We show that these temperature changes are likely to trigger abrupt responses in agricultural productivity and human mortality. Also there is a potential for a modest increase in seasonal mean monsoon rainfall with possible increase in frequency and intensity of extreme rain events. Increase in mean monsoon rainfall in the backdrop of increased El Nino like conditions would also indicate that the monsoon will be increasingly more difficult to predict. The conclusion on rainfall, however, comes with a considerable uncertainty. The projected anthropogenic climate changes are likely to have large impacts on key socio-economic sectors—agriculture and public health, which could have a pervasive negative effect throughout the entire economy barring appreciable mitigation efforts.

Reduction in uncertainty in projections of the monsoon hydrological cycle under different climate change scenarios and explicit handling of regional aerosols in the coupled models are crucial in order to meaningfully guide policy. It is therefore imperative that improving these biases of climate models in simulating the present day monsoon should be given high priority.

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